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Tensile and Creep Behaviour of Modified 9Cr-1Mo steel Cladding Tube for Fast Reactor using Metallic fuel

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Abstract

Modified 9Cr- 1Mo ferritic martensitic steel has been considered as cladding tube material in metallic fuel fast reactors in view of the relatively lower operating temperatures. In this study, tensile and creep behaviour of modified 9Cr-1Mo steel cladding tube have been investigated. Microstructure of the normalized and tempered steel consisted of tempered lath martensite with precipitates at the prior austenite grain boundaries and sub-boundaries. Tensile tests on the cladding tube were carried out at a strain rate of $3x10^{-3}$ s^{-1} over the temperature range of 300 - 923 K. The variations of 0.2 % yield stress, ultimate tensile strength and elongation of the steel with temperature have been studied. Yield stress and ultimate strength of the cladding tube exhibited plateau in the intermediate temperature range of 523 - 673 K, where the elongation exhibited a broad minimum. The tensile strength and ductility of the steel cladding tube were comparable with those reported for different products forms of the steel.

Creep properties of modified 9Cr-1Mo steel cladding tube were studied at 823 K at various stress levels. Creep curves of the steel generally consisted of primary and tertiary stages with no secondary stage of deformation. The variation of minimum creep rate with stress obeyed a power law. The stress exponent 'n' was around 25, which is the characteristic of precipitation hardened alloys. Rupture life was found to decrease with increase in stress. The Monkman-Grant relationship relating minimum creep rate with rupture life was found to be obeyed by the steel. Creep rupture strength of the modified 9Cr-1Mo steel cladding tube was in accordance with the reported values for other product forms.

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Keywords: metallic fuel, tempered martensite, creep deformation, Modified 9Cr-1Mo steel cladding tube, Monkman- Grant.

1. Introduction

9Cr–1Mo steel with additions of niobium, vanadium and nitrogen is called as modified 9Cr-1Mo Steel. Modified 9Cr-1Mo steel steel is a structural alloy developed for use as steam generator material for advanced fast

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breeder reactors. It is widely used in the power generation industry for tubing applications which require prolonged service at temperatures upto 873 K. Hence the study of the effect of the long term exposure on microstructure and on mechanical properties of this steel is essential. [1]. The long term creep properties of modified 9Cr–1Mo steel has been observed to be superior than the conventional steels with Cr content upto 9%Cr i.e., plain 9Cr–1Mo steel and 12Cr–1Mo–1W–0.3V steel [2-3]. The creep-rupture behaviour of modified 9Cr–1Mo steel is widely reported [2, 4-5] and the steel has been included in the various codes and standards including French nuclear design code RCC-MR [6].

Metallic fuel has been used in the sodium cooled fast breeder reactor. Fuel burn up of the fast reactor, is mainly limited by the void swelling and creep strength of the clad tube and void swelling of wrapper material. For improved burnup of fuel, material with better void swelling resistance and creep resistance is required. Modified 9Cr-1Mo steel ferritic steel has high void swelling resistance [7]. Creep resistance of the steel is not adequate in comparison with austenitic stainless steel. Hence this material can be used for the fast reactors with metallic fuel operating at lower temperatures.

In the present study the tensile properties of modified 9Cr-1Mo steel clad tubes were evaluated at a strain rate of $3x10^{-3}$/s in the temperature range 300-923 K and the creep properties were evaluated at 823 K at various stress levels to understand its mechanical behaviour.

2. Experimental

Modified 9Cr-1Mo steel clad tubes of length about 3 metres and outer diameter 6.7 mm, inner diameter 5.7 mm and 0.45 mm wall thickness were produced indigenously. These tubes were produced by cold pilgering and were normalized in the temperature range 1313-1363 K and cooled in air. Further they were tempered at 1053 K and cooled in air. The chemical composition of the clad tubes is given in table.1

Table.1. Chemical Composition (wt. %) of Modified 9Cr-1Mo steel clad tube.

C	Si	Mn	Cr	Mo	Ni	P	S	Al	Cu	N
0.12	0.36	0.45	8.92	0.98	<0.03	<0.01	0.004	<0.03	0.09	0.09
Ti	V	Nb	Sn	Sb	N/Al					
<0.01	0.19	0.06	<0.01	<0.01	>3					

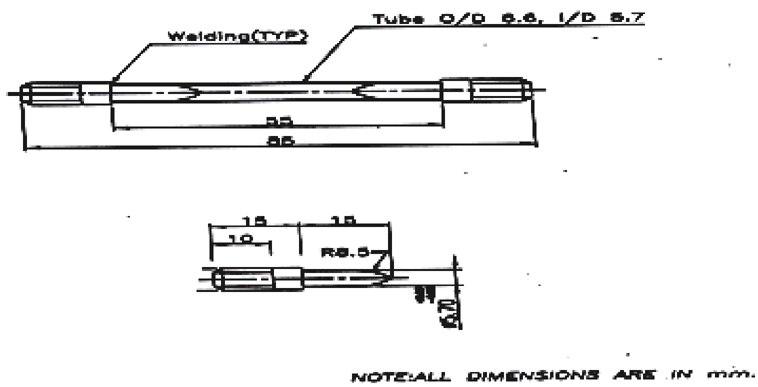


Fig.1: Tensile specimen design

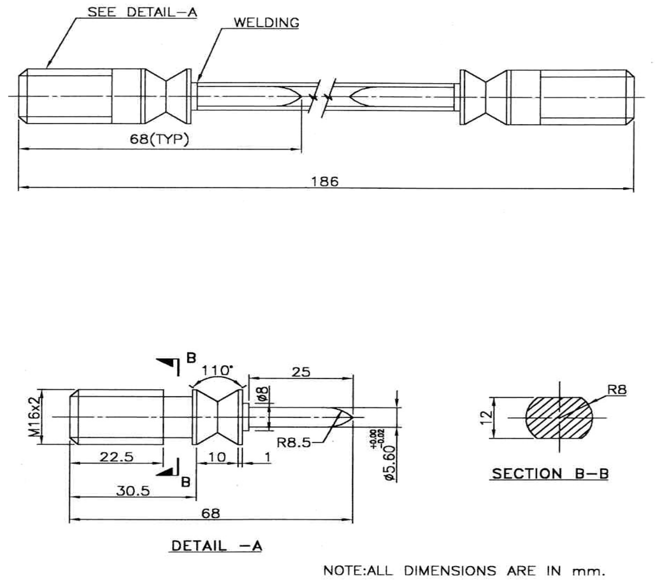


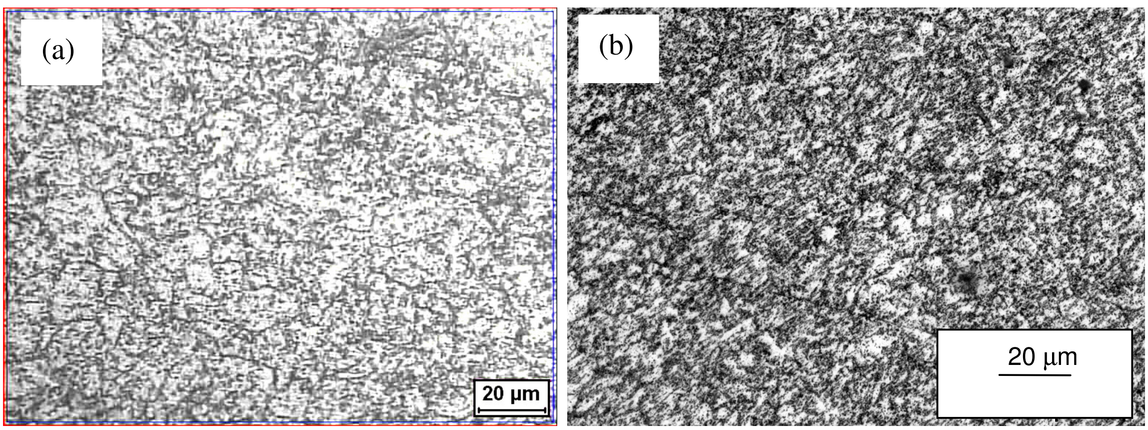
Fig.2: Creep specimen design

The tubes were cut into length of 100 mm and welded with mandrels (holders) by tungsten inert gas (TIG) welding. Specimen designs for tensile and creep testing is shown in figures 1 and 2. The tensile properties of modified 9Cr-1Mo steel clad tubes were evaluated at a strain rate of $3x10^{-3}$/s in the temperature range 300-923 K and the creep properties were evaluated at 823 K at various stress levels to understand the mechanical behaviour.

3. Results and Discussion

3.1 Microstructures

Figure 3(a) shows the microstructure of the clad tube in the as-received condition. The microstructure in this condition is tempered lath martensite. The microstructure developed after creep testing for nearly 8000 hours consisted of coarse precipitates (fig. 3(b)). The scanning electron micorograph of the specimen tested for nearly 30 hours, showing tempered martensite laths and precipitates is shown in figure 3(c).



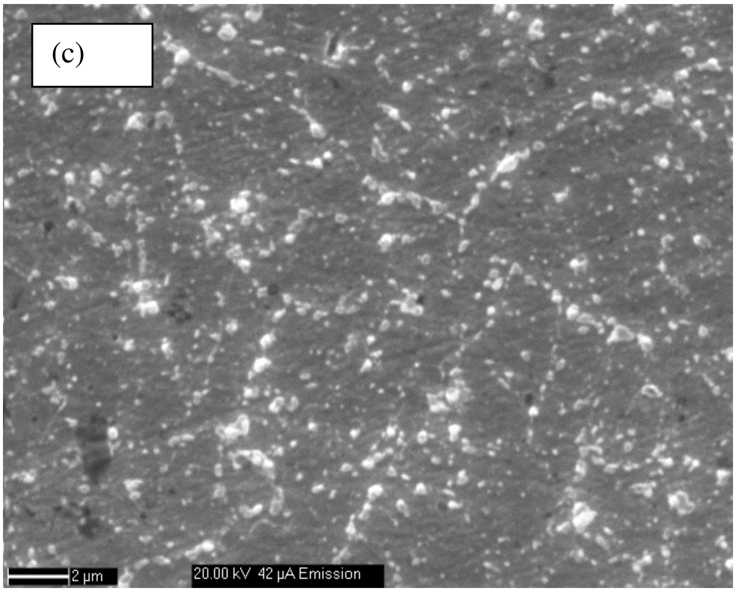


Fig.3 (a). Microstructure of the modified 9Cr-1Mo steel in the as-received conditiond (b) microstructure after creep testing for nearly 8000 hours (c) Scanning electron micrograph of the creep tested specimen for nearly 30 hours.

The fracture surfaces of the steel after creep testing for nearly 30 hrs and 8000 hours are shown in figures 4(a) and 4(b) respectively. The fracture surfaces of the steel tested at these conditions were found to contain dimples indicating transgranular failure resulting from the coaelsence of microvoids. The rupture elongation in these conditions varied between 20-25%.

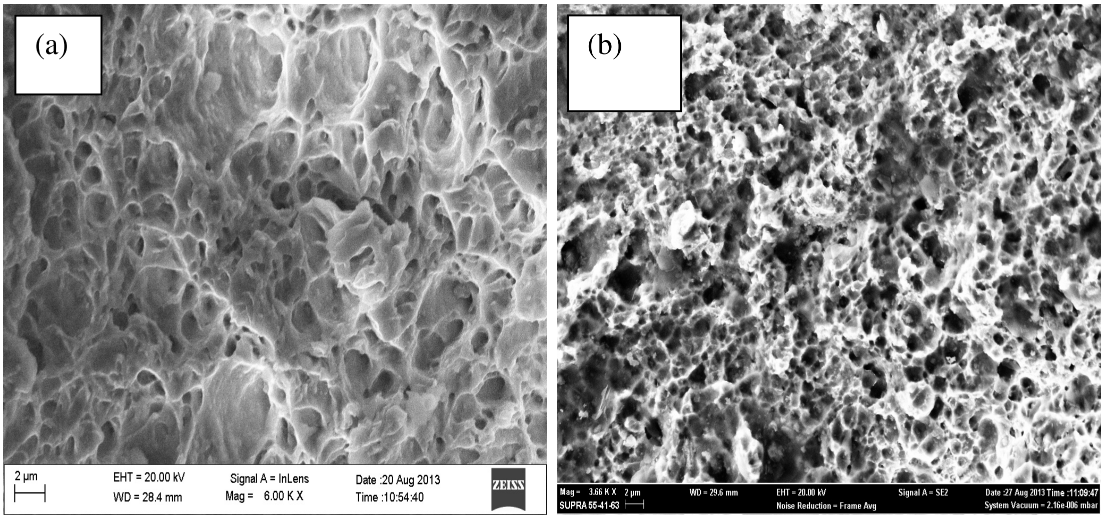


Fig.4.Fracture surface of the modified 9Cr-1Mo steel tested at 823 K (a) at 280 MPa: rupture life 30 hrs (b) at 210 MPa: rupture life 8000 hrs.

3.2 Tensile Deformation Behaviour

The engineering stress-strain curves for the modified 9Cr-1Mo steel clad tubes at a strain rate of 3 x 10^{-3} s^{-1} over a temperature range of 300 - 923 K are shown in Fig.5. The stress- strain curves at 300 K were smooth. However, serrated flow curves were observed at intermediate temperatures in range of 523 - 673 K. The serrations observed in this study were mainly of type E [8]. Serrated yielding was observed in 9Cr-1Mo steel in the temperature range 523-673 K by several authors [9-11]. Smooth load elongation curves were observed at higher temperatures. The variations of yield stress (YS) and ultimate tensile strength (UTS) of the steel with test temperature are shown in figures 6 and 7. The data obtained from NIMS Japan [12] on modified 9Cr-1Mo steel tubes is also shown in the figure. Ultimate tensile strength of the steel decreased with increase in temperature. The plateau region was observed in the intermediate temperature range (423-673 K), rapid rate of decrease in strength was observed with further increase in temperature beyond 673 K.

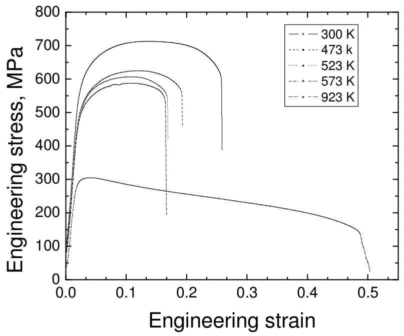


Fig.5. Engineering stress-strain curves at various temperatures.

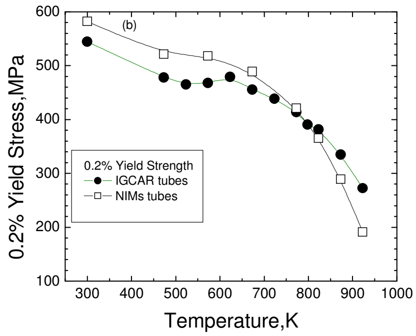


Fig.6. Variation of 0.2% yield stress with test temperature.

The ductility measured in terms of total elongation showed lower values in the intermediate temperature range, followed by a relatively rapid increase above 673 K. In steels, a plateau region is observed in variation of tensile properties, such as YS, UTS, percentage elongation, with temperature in the intermediate temperature range, which has been reported to be associated with the occurrence of dynamic strain aging [13-14]. Serrated tensile flow behavior is one of the several manifestations of DSA [8] and the same was observed in the present investigation. Slower rate of decrease in tensile strength (Fig. 6 and 7) along with ductility minima (Fig.8) has been attributed to the occurrence of dynamic strain ageing.

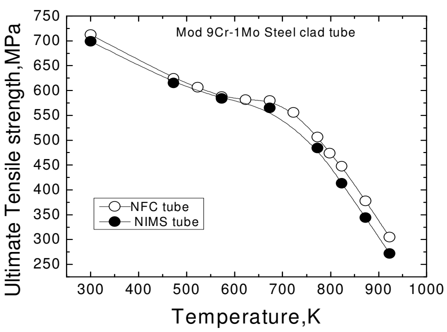


Fig.7. Comparison of ultimate tensile strengths of IGCAR and NIMS clad tubes.

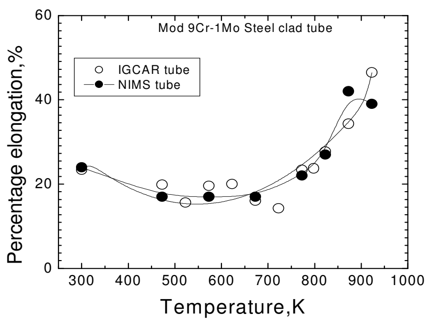


Fig.8. Comparison of total elongation of IGCAR and NIMS clad tubes.

3.3 Creep Deformation Behavior

The creep curves at various stress levels are shown in Fig.9. The creep curves are characterized by small instantaneous strain on loading, a short primary region, and extended tertiary regions. The variation of creep rate with time is shown in figure 10 for various stress levels. A minimum in creep rate was observed for all the stress levels.

The variation of minimum creep rate with applied stress is shown in Fig.11. The relation between minimum creep rate and applied stress exhibited a power law of the form

$$\dot{\varepsilon}_m = A\sigma^n \qquad (1)$$

Where $\dot{\varepsilon}_m$ is the minimum creep rate, A is a constant σ is the applied stress and n is the stress exponent. The stress exponent value of 25 obtained in this study is characteristic of precipitation hardened alloys. The value of stress exponent is high compared to that of dislocation climb controlled models of power law creep. A stress exponent of 15 at 873 K has been observed by Spigarelli and Quadrant [15] for the steel. Kimura et al [16] reported high values of stress exponent of 16 at 823 K and 12 at 873 K at high stresses for modified 9Cr–1Mo steel. Figure 12 shows the variation of rupture life with applied stress. Rupture life decreased with increase in applied stress.

A comparison of creep strength of modified 9Cr-1Mo steel fuel clad tube (obtained in this study) with those of modified 9Cr-1Mo steel steam generator [17] and NIMS [12] reported values are shown in figure 13. The longest rupture life obtained in this study was around 8000 hours. The RCC-MR [18] average values of creep rupture stress, maximum allowable stress and minimum creep rupture stress are also shown in the figure. It can be seen from the figure that the creep rupture stress of IGCAR tubes follows RCC-MR average stress value. The creep strengths of modified 9Cr-1Mo steel clad tubes were found to compare well with steam generator tubes and NIMS tubes.

The variation of rupture elongation with rupture life is shown in Fig.14. The elongation values are compared with those of NIMS tubes. In general a marginal increase in rupture elongation with rupture life was observed.

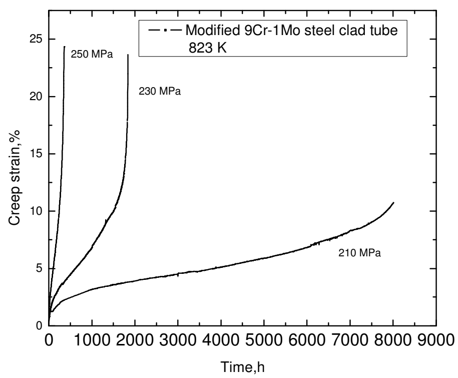


Fig.9. Creep Curves at various stress levels.

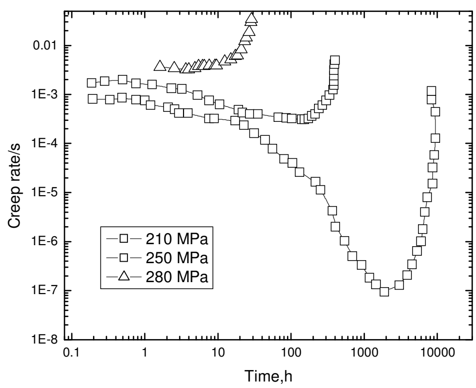


Fig.10. Variation of creep rate with time.

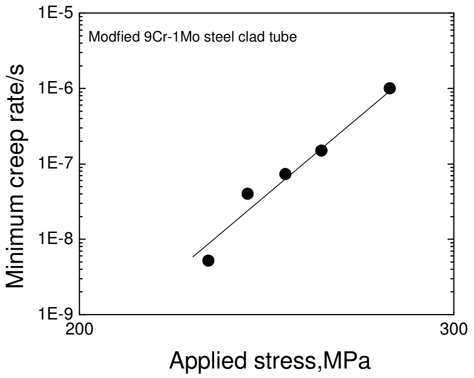


Fig.11. Stress dependence of minimum creep rate at 823 K.

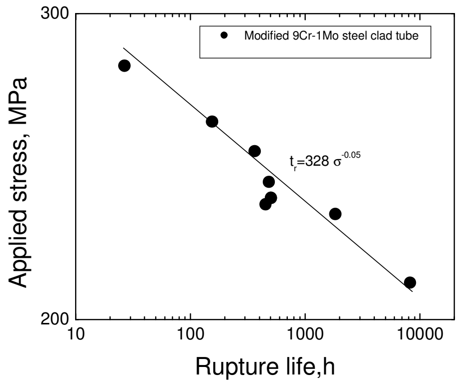


Fig.12. Variation of rupture life with applied stress at 823 K.

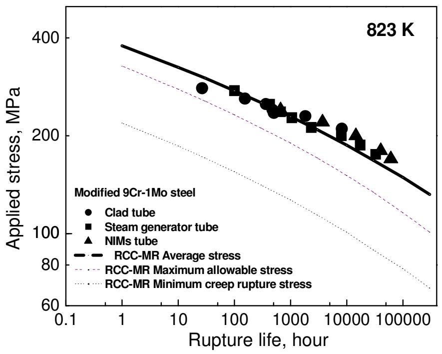


Fig.13.Comparison of creep strengths of Modified 9Cr-1Mo steel clad tubes with steam generator tubes [17], NIMS tubes [12] and RCC-MR values [18].

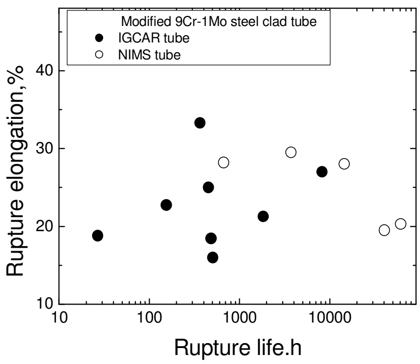


Fig.14. Variation of rupture elongation with rupture life.

3.4 Relation between Deformation and Fracture

The relation between minimum creep rate and rupture life is described by Monkman- Grant relationship [19] which is given as

$$\dot{\varepsilon}_m{}^{\alpha} t_r = C \qquad (2)$$

where $\dot{\varepsilon}_m$ is the minimum creep rate, t_r, is the rupture life α and C are constants. The validity of Monkman- Grant relation is shown in figure 15.The value of α is around 0.8 and C around 0.5, which is consistent with many materials [20]. For materials which exhibit longer tertiary creep, Dobes and Millika [21] proposed a relation

$$\dot{\varepsilon}_m{}^{\alpha'} t_r / \varepsilon_T = C' \quad (3)$$

where ε_T the rupture is strain and C' is the modified Monkman- Grant constant. The modified Monkman Grant plot is shown in figure 16.The value of α' is around 0.8. The modified Monkman–Grant values, as described by Eq. (3) has been evaluated for several alloys including stainless steel 304 [22], Ni-based super alloy [23], Cr–Mo steels [24, 17], oxide dispersion strengthened (ODS)–alloy and Grade 91 steel [25-26] and ferritic–martensitic steel HT9 [27].

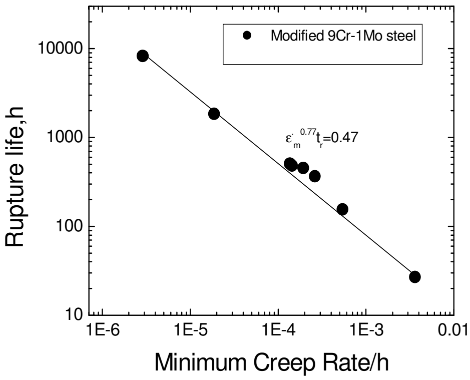


Fig.15. Validity of Monkman- Grant relationship.

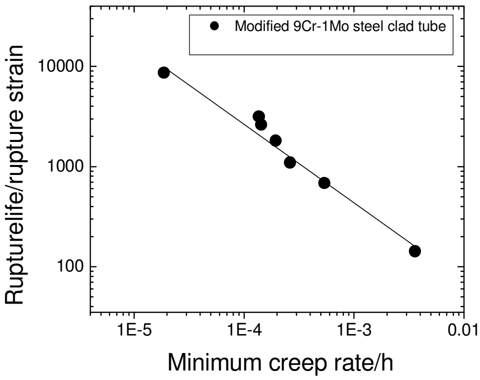


Fig.16. Validity of modified Monk man- Grant relationship.

4. Conclusions

1. Yield stress and ultimate strength of modified 9Cr-1Mo steel clad tube exhibited plateau in the intermediate temperature range of 523 - 673 K, where the elongation exhibited a broad minimum. Dynamic strain ageing manifested as serrations in the tensile curve were observed in is temperature range.

2. The creep curves were characterized by a small primary and an extended tertiary region with no secondary stage of deformation.

3. The variation of minimum creep rate with applied stress obeyed a power law. Creep strengths of these tubes are comparable with that of internationally reported values.

4. The steel obeyed Monkman- Grant and Modified Monkman- Grant relationship. The fracture surfaces were characterized by dimples.

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